REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
20-04-2012	Final Technical Report	15 Apr 08 - 30 Dec 11

4. TITLE AND SUBTITLE
Device Technologies for Semiconductor Spintronic Circuits

5a. CONTRACT NUMBER

5b. GRANT NUMBER
N00014-08-1-0859

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
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5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

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8. PERFORMING ORGANIZATION REPORT NUMBER
ELEG332265-20120420

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
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Suite 4R15
Atlanta, GA 30303-3104

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited.

20120430004

13. SUPPLEMENTARY NOTES

14. ABSTRACT
The goal of this project was to develop spin injection and detection techniques to enable spin transport to enhance the speed and design of CMOS VLSI circuits. Progress toward this goal over the duration of the award specifically impacts: (1) Understanding extrinsic origins of spin depolarization at interfaces and with localized impurity states; and (2) Quantifying the extent to which physical processes and boundary conditions affect spin dephasing in vertical-transport devices. The results of these efforts were the following. We analytically derived the impulse response (Green's function) of a current-sensing spin detector. We showed that spin diffusion and concomitant spin dephasing could be greatly enhanced with respect to charge diffusion. We showed that strong spin relaxation at oxide interfaces yielded a spin lifetime of ~1ns, orders of magnitude lower than lifetimes in bulk Si. Experimental evidence of spin precession during travel through the doped Si channels indicated delays associated with electron capture or reemission in shallow impurity traps. These results helped to significantly improve the understanding of spin transport in silicon.

15. SUBJECT TERMS
Spintronics, spin transport in silicon, spin transport modeling, spin dephasing, spin relaxation

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
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Device Technologies for Semiconductor Spintronic Circuits

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April 20, 2012

Final report: N00014-081-1-0859 "Device Technologies for Semiconductor Spintronic Circuits"

The goal of this project was to develop spin injection and detection techniques to enable spin transport to enhance the speed and design of CMOS VLSI circuits. Progress toward this goal over the duration of the award specifically impacts 1. Understanding extrinsic origins of spin depolarization at interfaces and with localized impurity states; and 2. Quantifying the extent to which physical processes and boundary conditions affect spin dephasing in vertical-transport devices. We summarize the results of these efforts below:

Spin transport modeling: By incorporating the proper boundary conditions, we analytically derived the impulse response (or "Green's function") of a current-sensing spin detector. We also compare this result to a Monte Carlo simulation (which automatically takes the proper boundary condition into account) and an empirical spin transit time distribution obtained from experimental spin precession measurements. In the strong drift-dominated transport regime, this spin *current* impulse response can be approximated by multiplying the spin *density* impulse response by the average drift velocity. However, in weak drift fields, large modeling errors up to a factor of 3 in most-probable spin transit time can be incurred unless the full spin current Green's function is used. [Ref. 1 below]

Understanding spin dephasing: Drift-diffusion theory – which fully describes charge transport in semiconductors – is also universally used to model transport of spin-polarized electrons in the presence of longitudinal electric fields. By transforming spin transit time into spin orientation with precession (a technique called the "Larmor clock") in current-sensing vertical-transport intrinsic Si devices, we have shown that spin diffusion and concomitant spin dephasing can be greatly enhanced with respect to charge diffusion, in direct contrast to predictions of spin Coulomb-drag diffusion suppression. [Ref. 2 below]

Spin relaxation at Si/SiO_2 interface: Using a two-dimensional finite-differences scheme to model spin transport in silicon devices with lateral geometry, we simulated the effects of spin relaxation at interfacial boundaries, i.e., the exposed top surface and at an electrostatically-controlled backgate with a SiO_2 dielectric. These gate-voltage-dependent simulations were compared to previous experimental results and Hall effect measurements and show that strong spin relaxation, due to extrinsic effects, yields a Si/SiO_2 interfacial spin lifetime of ~1ns, orders of magnitude lower than lifetimes in the bulk Si. [Ref. 3 below]

Transient impurity trapping: Experimental evidence of electron spin precession during travel through the phosphorus-doped Si channel of an all-electrical device simultaneously indicates two distinct processes: (i) short time scales (≈50 ps) due to purely conduction-band transport from injector to detector and (ii) long time scales (≈1 ns) originating from delays associated with capture or reemission in shallow impurity traps. The origin of this phenomenon, examined via temperature, voltage, and electron density dependence measurements, was established by means of a comparison to a numerical model and is shown to reveal the participation of metastable excited states in the phosphorus-impurity spectrum. [Ref. 4 below]

Publications acknowledging support from ONR through this DEPSCoR award:

1. Jing Li, and Ian Appelbaum, "Modeling spin transport with current-sensing spin detectors", Appl. Phys. Lett. **95**, 152501 (2009).
2. Biqin Huang and Ian Appelbaum, "The Larmor clock and anomalous spin dephasing in silicon", Phys. Rev. B Rapid Comm. **82**, 241202(R) (2010). ("Editor's Suggestion")
3. Jing Li and Ian Appelbaum, "Interfacial spin relaxation in electrostatically-gated lateral-transport silicon devices", Phys. Rev. B **84**, 165318 (2011).
4. Yuan Lu, Jing Li, and Ian Appelbaum, "Spin-Polarized Transient Electron Trapping in Phosphorus-doped Silicon", Phys. Rev. Lett. **106**, 217202 (2011).